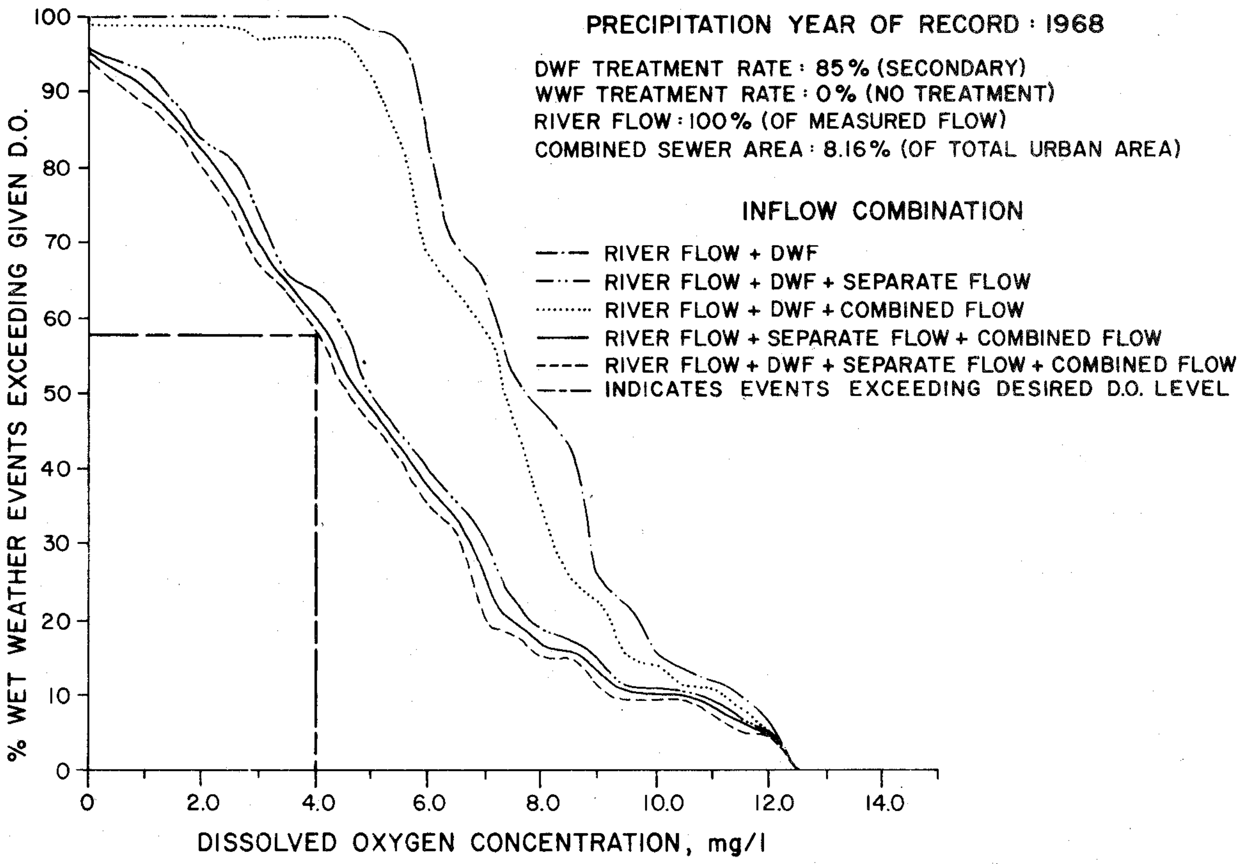


Figure VII-10. Minimum DO Frequency Curves for Existing Conditions in the Des Moines River

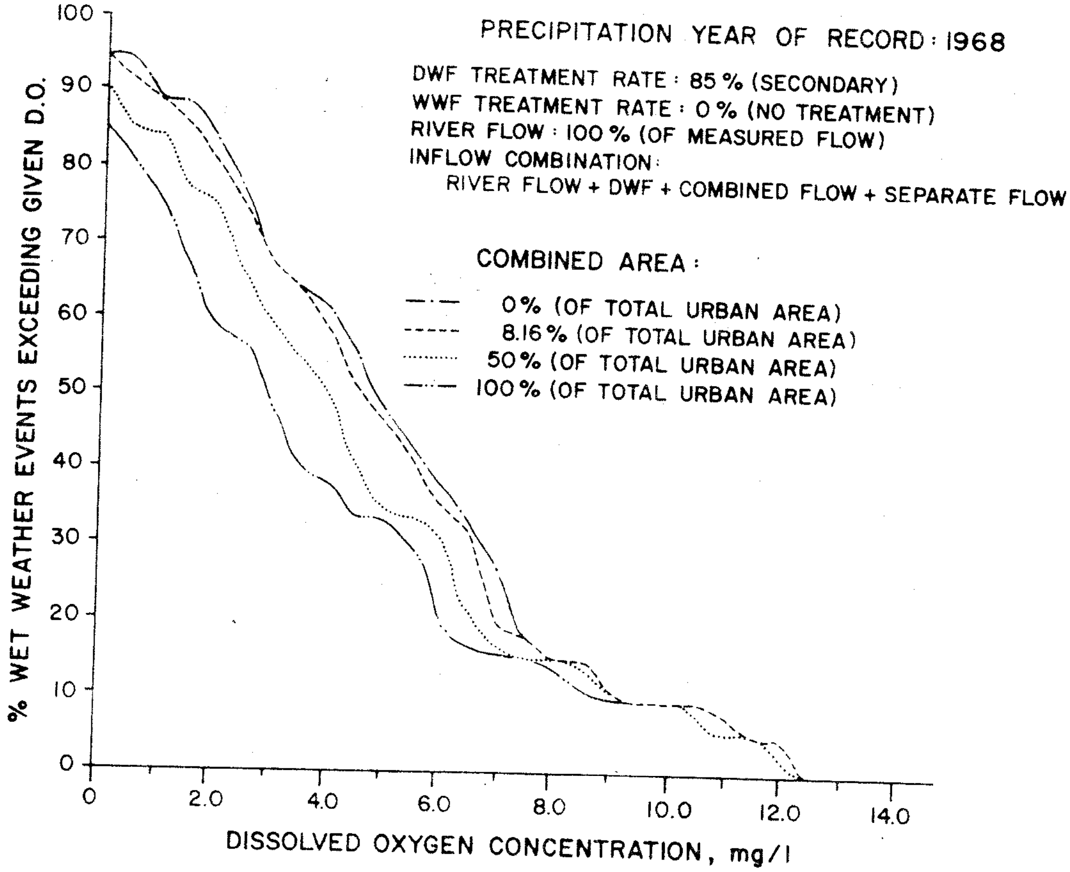


Figure VII-11. Minimum DO Frequency Curves for Varied Percent of Combined Sewer Area

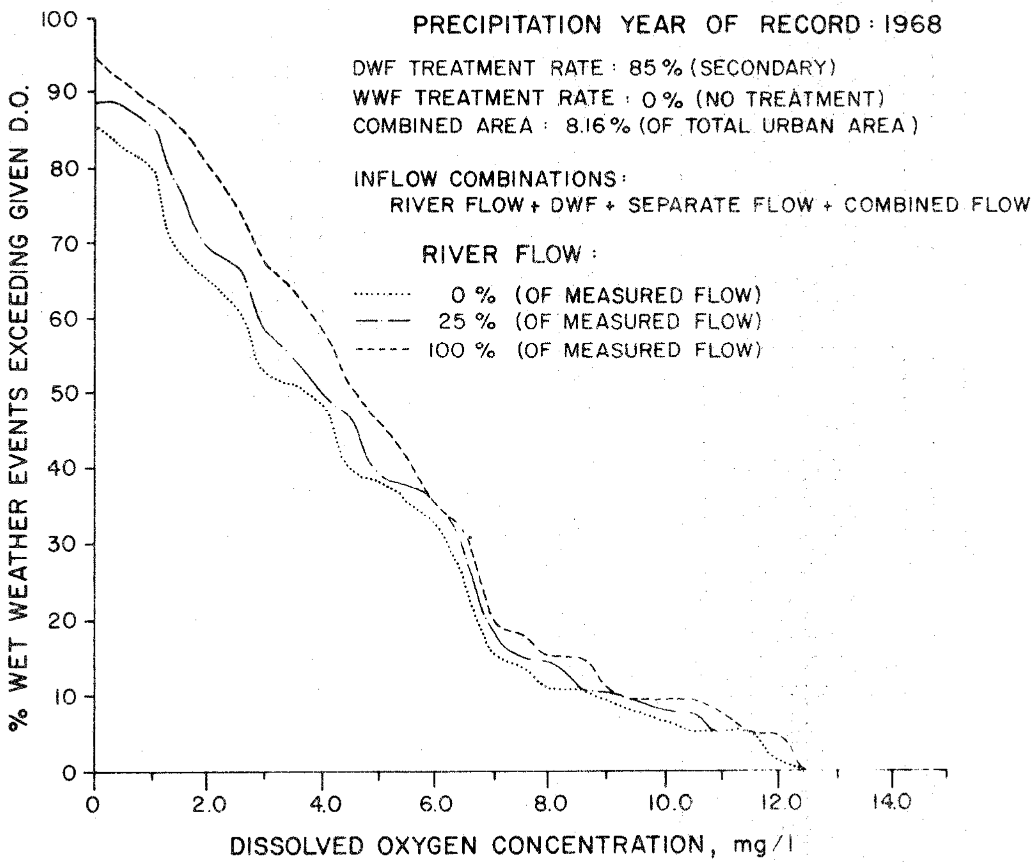


Figure VII-12. Minimum DO Frequency Curves for Varied Percent of Actual Measured Upstream River Flow

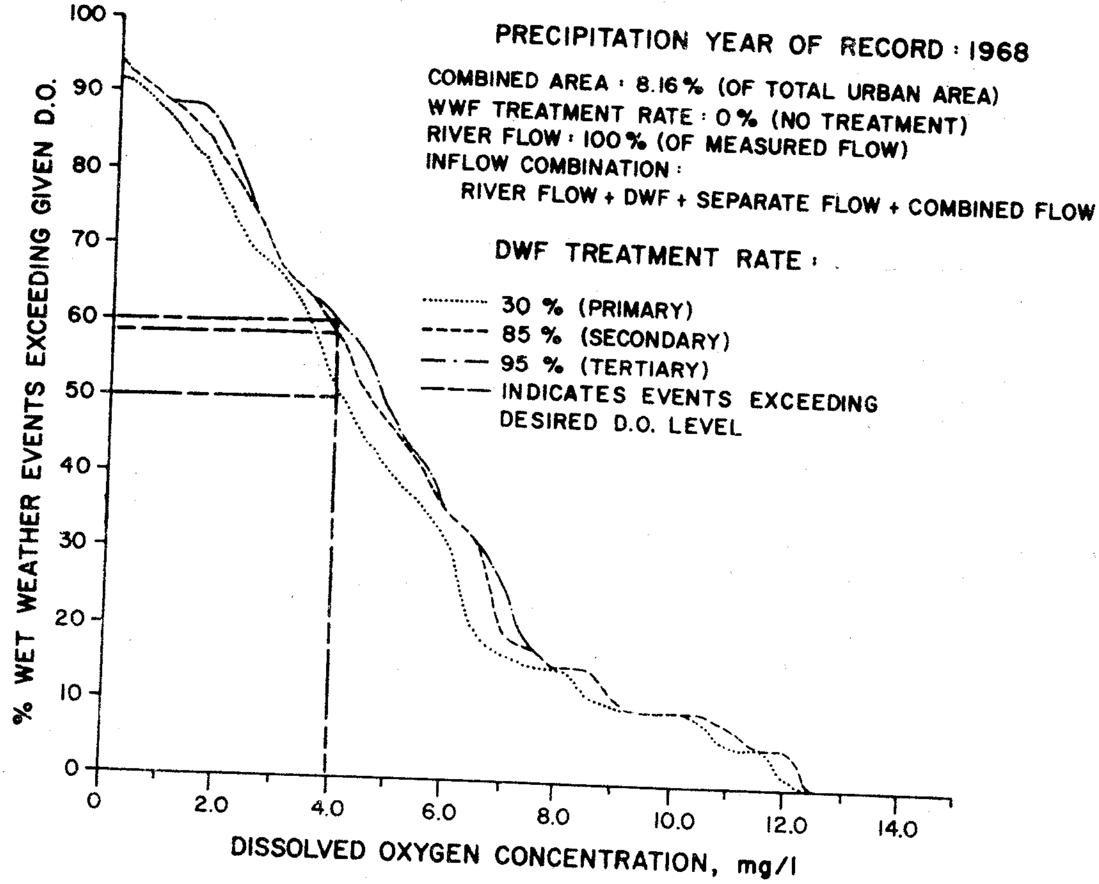


Figure VII-13. Minimum DO Frequency Curves for Varied DWF Treatment

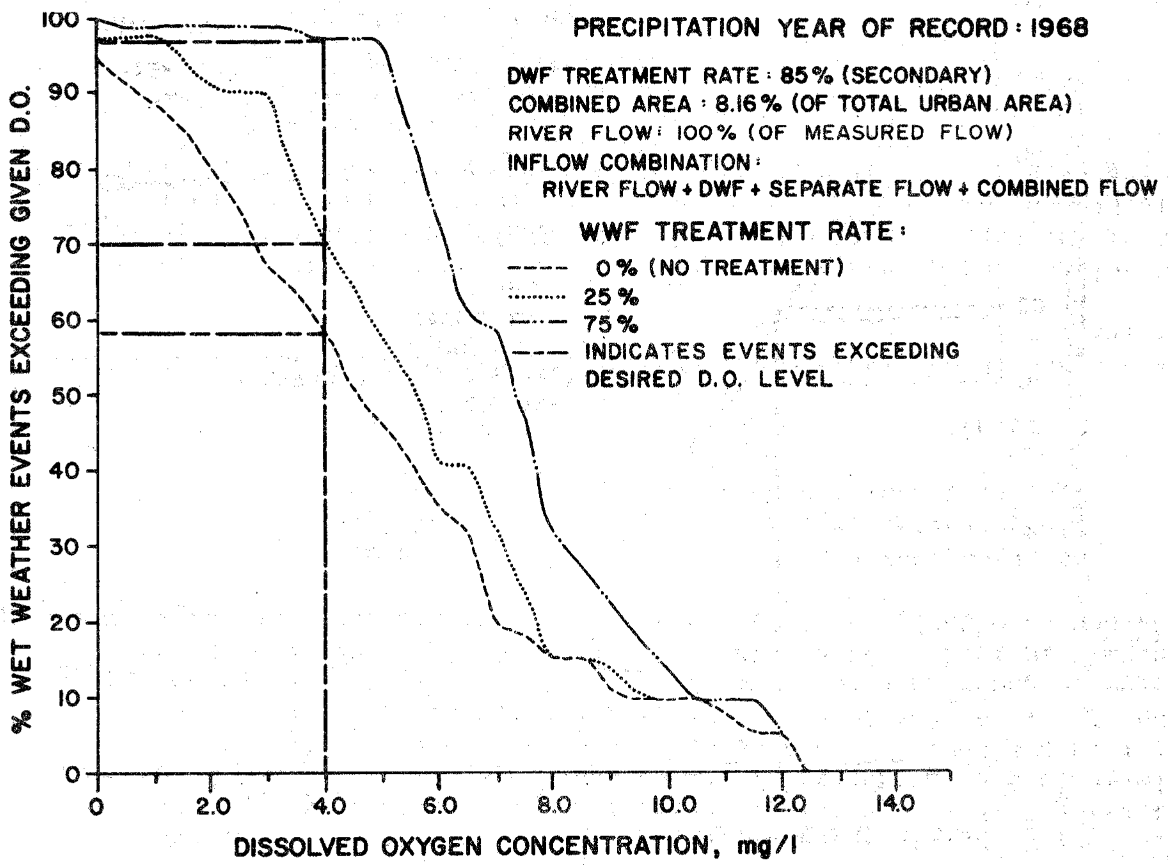


Figure VII-14. Minimum DO Frequency Curves for Varied WWF Treatment

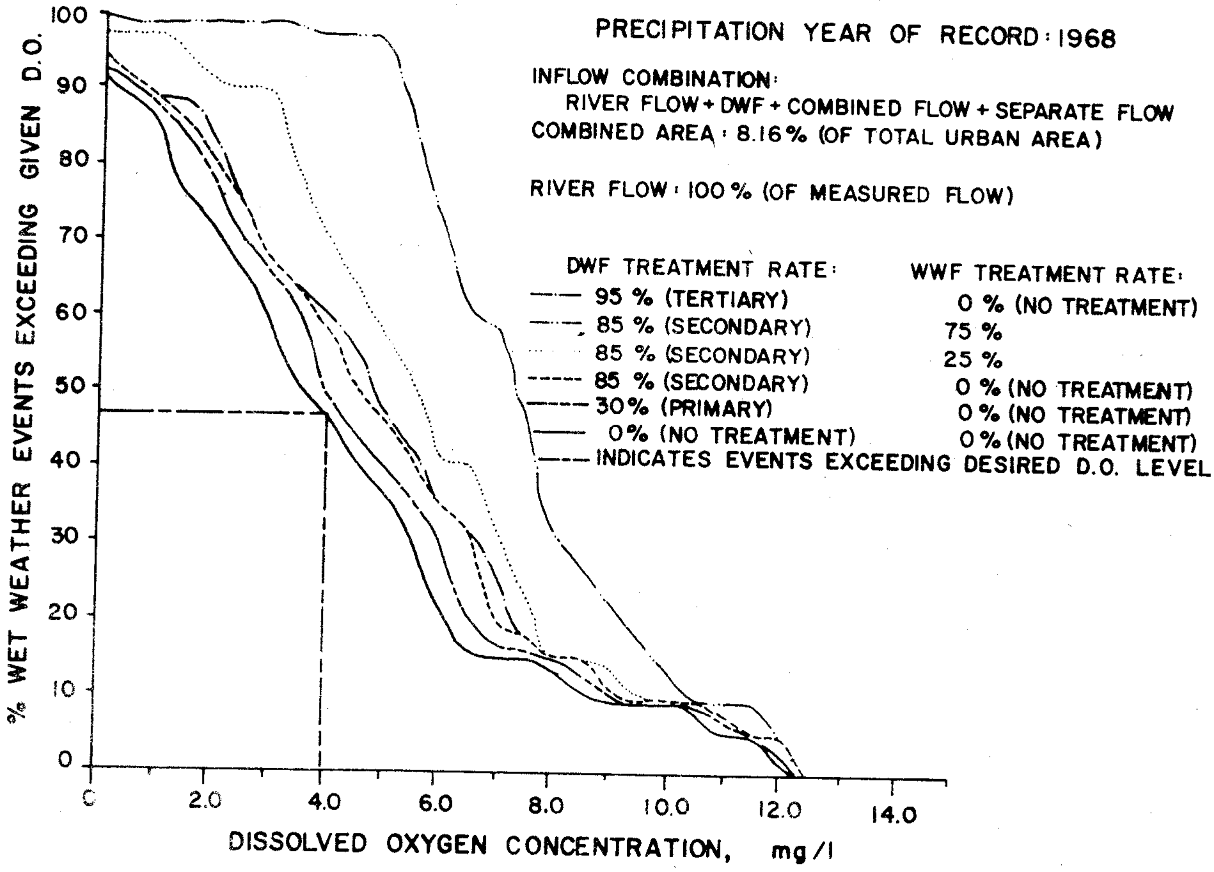


Figure VII-15. Minimum DO Frequency Curves for Varied Treatment Alternatives

1. for all of the precipitation events defined by the model, upstream river flow was on the average 50 percent of the total river flow; and

2. this percentage ranged from as low as 6 percent to as high as 97 percent of total river flow.

For the Des Moines application, and the particular rainfall year selected (1968), urban runoff seems to be the key factor in receiving water critical DO levels. However, an urban area located very far upstream in a river basin would have a more detrimental impact on water quality downstream from the urban area than if the same urban area was located on a higher order stream within the network.

Figure VII-13 shows the effect of varying the degree of treatment of DWF while holding the other parameters constant. It can be inferred that there is no significant improvement of stream water quality (DO) by upgrading DWF treatment from secondary to tertiary during periods of wet weather. However, it is clear that the improvement in minimum DO levels by upgrading DWF treatment from primary to secondary is probably worthwhile: 7 percent more wet-weather events would exceed a DO value of 4.0 mg/l. Examination of Figure VII-14 reveals that critical DO levels are improved appreciably with 25 percent treatment of WWF and markedly with 75 percent treatment of WWF, while providing secondary treatment of DWF. The minimum DO frequency curves in Figure VII-15 compare four treatment alternatives to reduce water pollution during periods of urban runoff:

1. 95 percent treatment of DWF and no treatment of urban runoff,

2. 85 percent treatment of DWF and 25 percent treatment (BOD removal) of WWF,

3. 85 percent treatment of DWF and 75 percent treatment of WWF, and

4. 85 percent treatment of DWF and no treatment or urban runoff.

The zero treatment and primary treatment curves are also shown for comparison, but are not considered acceptable alternatives. It appears that options 1 and 4 above result in comparable critical DO levels in the receiving stream. However, options 2 and 3 result in much more improved critical DO levels. An economic evaluation of these treatment alternatives, on an annual basis, is presented in a later subsection.

It is now appropriate to examine the results of applying the model to periods throughout the year during which no urban runoff was produced. Dry weather was experienced for approximately 300 days throughout 1968. The model was applied to these periods using a daily time step. This modification is certainly justified since conditions are more truly steady-state than during periods of precipitation and subsequent runoff: for example, waste loadings (DWF treatment plant effluent) and river flow do not vary as much during the day. For the dry-weather simulation period, upstream river flow was on the average 94 percent of total river flow, ranging from 82 percent to 99.6 percent. The results are shown in Figure VII-16, Dry-Weather Minimum DO Frequency Curves for Varied DWF Treatment Alternatives. A remarkable 97 percent of the dry-weather days exceed a minimum DO concentration of 4.0 mg/l. Upgrading of DWF treatment becomes meaningful only if stream DO standards are set higher than 4.0 mg/l. From Table VII-3, it is clear that the Des Moines River in particular carries a high BOD load upstream of the Des Moines urban area. This explains why, even during dry-weather periods only, a significant increase in the DWF treatment rate does not result in a corresponding increase in the critical DO levels, as shown in Figure VII-16.

To maintain the proper perspective, it is desirable to view the effects of urban runoff on an annual basis, not just during periods of wet weather. The frequency curves shown in Figures VII-15 and VII-16 are combined by weighting on the basis of the number of rainfall days and dry-weather days in the year. The composite totals are presented in Figure VII-17, Annual Minimum DO Frequency Curves. For example, a given stream standard of 4.0 mg/l is exceeded 90 percent of the time for existing conditions in Des Moines, Iowa, throughout the year 1968. A significant amount of treatment (75% BOD removal) of WWF in addition to secondary treatment of DWF results in critical DO levels such that the same stream standard is exceeded 97 percent of the days in the year. Annual DO duration curves tend to mask the impact of shock loads of organic pollutants discharged during periods of urban runoff. A few extended violations of stream DO standards may cause anaerobic conditions resulting in fish kills and proliferation of undesirable microorganisms.

The integral of the DO deficit equation over all time, equation VII-31, has been suggested as a measure of the relative effect of one waste source versus another. Denoted as $\mathcal{V}$, the volume of DO deficit, this parameter is computed for each treatment option during both wet- and dry-weather periods. The average values obtained are given in Table VII-6, Volume of DO Deficit. The results indicate the same ranking of the treatment alternatives as suggested by the curves in Figure VII-17, from a water quality viewpoint. This implies that the integrated DO deficit, $\mathcal{V}$, may provide a simple method of comparing the impact upon receiving waters of alternative input configurations. However, interpretation of the numerical value of $\mathcal{V}$, in an absolute sense, remains ambiguous.

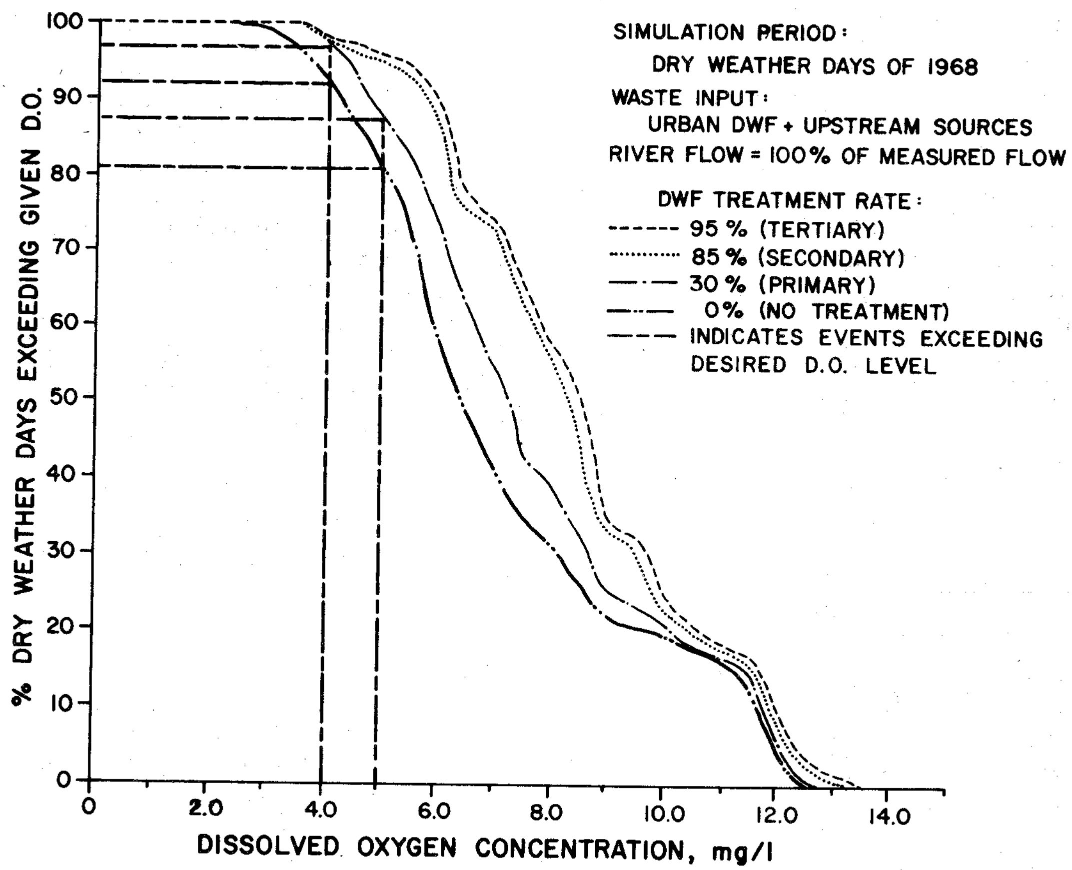


Figure VII-16. Dry-Weather Minimum DO Frequency Curves for Varied DWF Treatment Alternatives

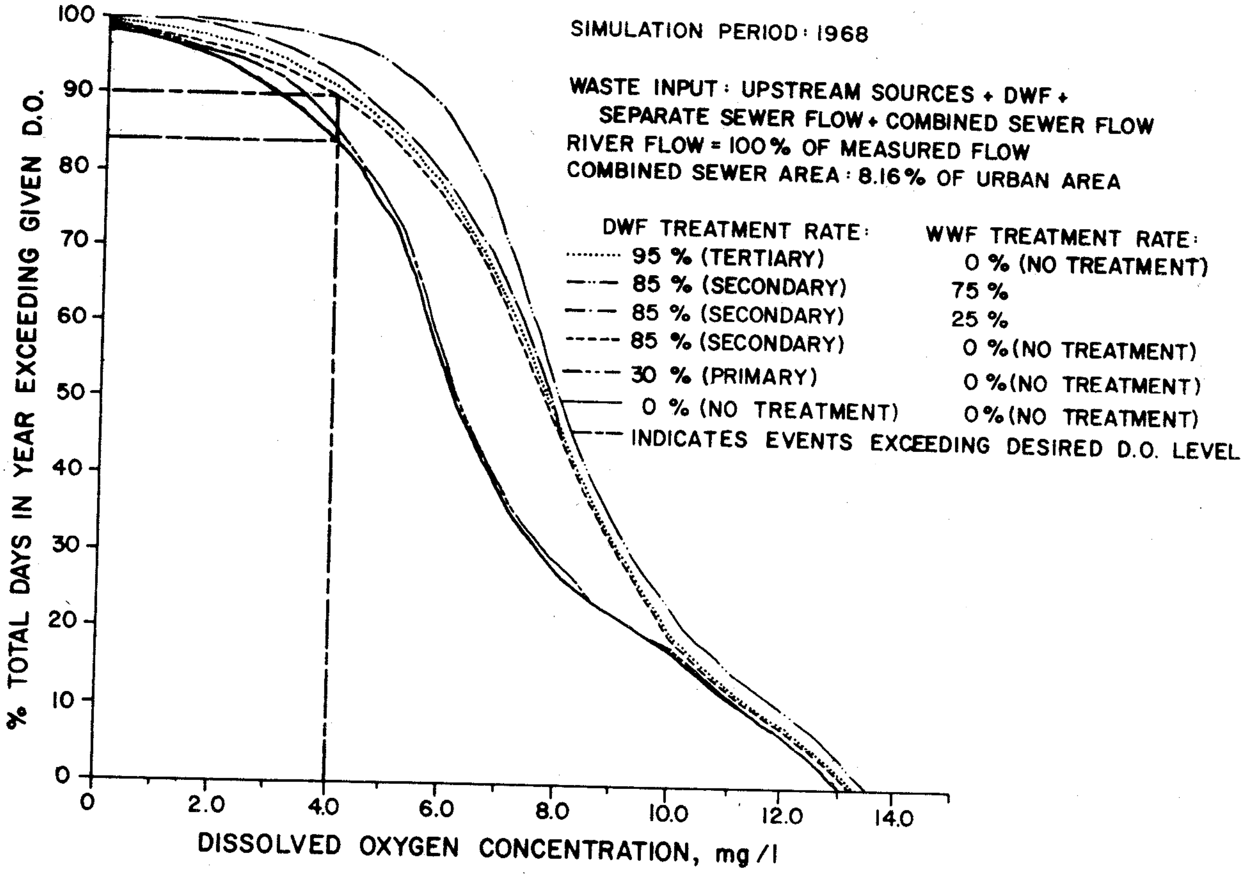


Figure VII-17. Annual Minimum DO Frequency Curves

Table VII-6. VOLUME OF DO DEFICIT[a]

Option	DWF Treatment Rate (% BOD Removal)	WWF Treatment Rate (% BOD Removal)	Average $\forall$ for Wet Periods (mg-day/l)	Average $\forall$ for Dry Periods[c] (mg-day/l)	Average $\forall$ Year (mg-day/l)
1	95 (Tertiary)	0 (No Treatment)	31.5	6.3	10.8
2	85 (Secondary)	75 (Biological, Physical, Chemical)	12.6	7.3	8.3
3	85 (Secondary)	25 (Physical)	25.6	7.3	10.6
4[b]	85 (Secondary)	0 (No Treatment)	32.1	7.3	11.7
5	30 (Primary)	0 (No Treatment)	35.5	12.8	16.8
6	0 (No Treatment)	0 (No Treatment)	37.3	16.0	19.8

[a] $\forall = \frac{D_o + L_o}{K_2}$

[b] Existing conditions in Des Moines, Iowa.

[c] Values correspond to DWF treatment rate only.

ECONOMIC EVALUATION OF TREATMENT ALTERNATIVES

Alternatives

Two major alternatives to existing conditions are considered in this section:

1. upgrading the existing DWF treatment facility from a high-rate trickling filter plant to a tertiary treatment process, or

2. providing two separate levels of urban stormwater runoff control

   i. 25 percent BOD removal, or
   ii. 75 percent BOD removal,

   while maintaining existing DWF removal efficiencies.

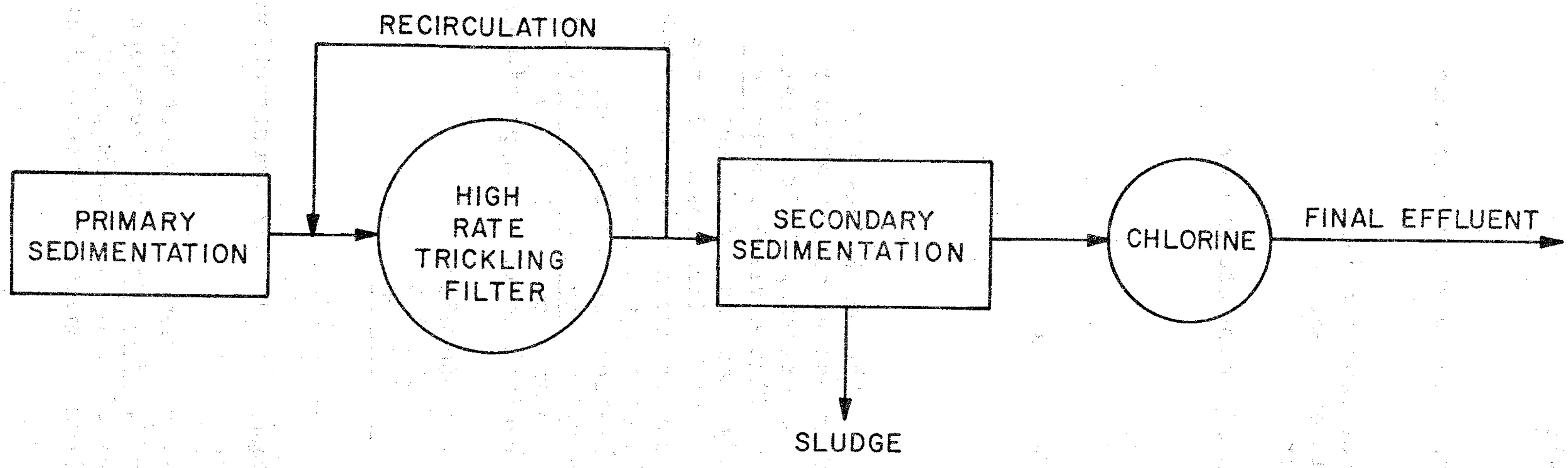
Upgrading DWF Treatment

To achieve a tertiary treatment configuration, the Des Moines DWF treatment facility must undergo an intermediate-stage modification to activated sludge. A simplified profile of the existing DWF treatment plant and its characteristics is presented in Figure VII-18, Existing DWF Process Profile. When an activated sludge unit is added, the trickling filter acts as a roughing filter. The capital costs of this intermediate-stage upgrading are evaluated separately and must be added later to the capital costs associated with a tertiary treatment capability. A profile of the trickling filtration/activated sludge system is shown in Figure VII-19, Trickling Filtration/Activated Sludge System. In 1975 dollars (ENR 2200), for a design flow of 35.3 mgd (134,000 cu m/day), the intermediate-stage capital costs are approximately:[18]

Aeration Tank(s)	$1,560,026
Sludge Recirculation	574,746
Clarifier Modifications	88,000
Total	$2,222,772

These costs do not include engineering design, bonding, and construction supervision.

The unit processes added to achieve tertiary treatment (95 percent BOD removal or better) are shown in Figure VII-20, Added Tertiary Treatment Unit Processes. It is assumed that disposal of chemical sludge is by incineration. Cost figures were obtained from a report by Battelle-Pacific



DESIGN FLOW: 35.3 MGD

POP. SERVED: 247,920

BOD INFLUENT: 325 mg/l

BOD EFFLUENT: 49 mg/l

% BOD REMOVAL: 85

Figure VII-18. Existing DWF Process Profile

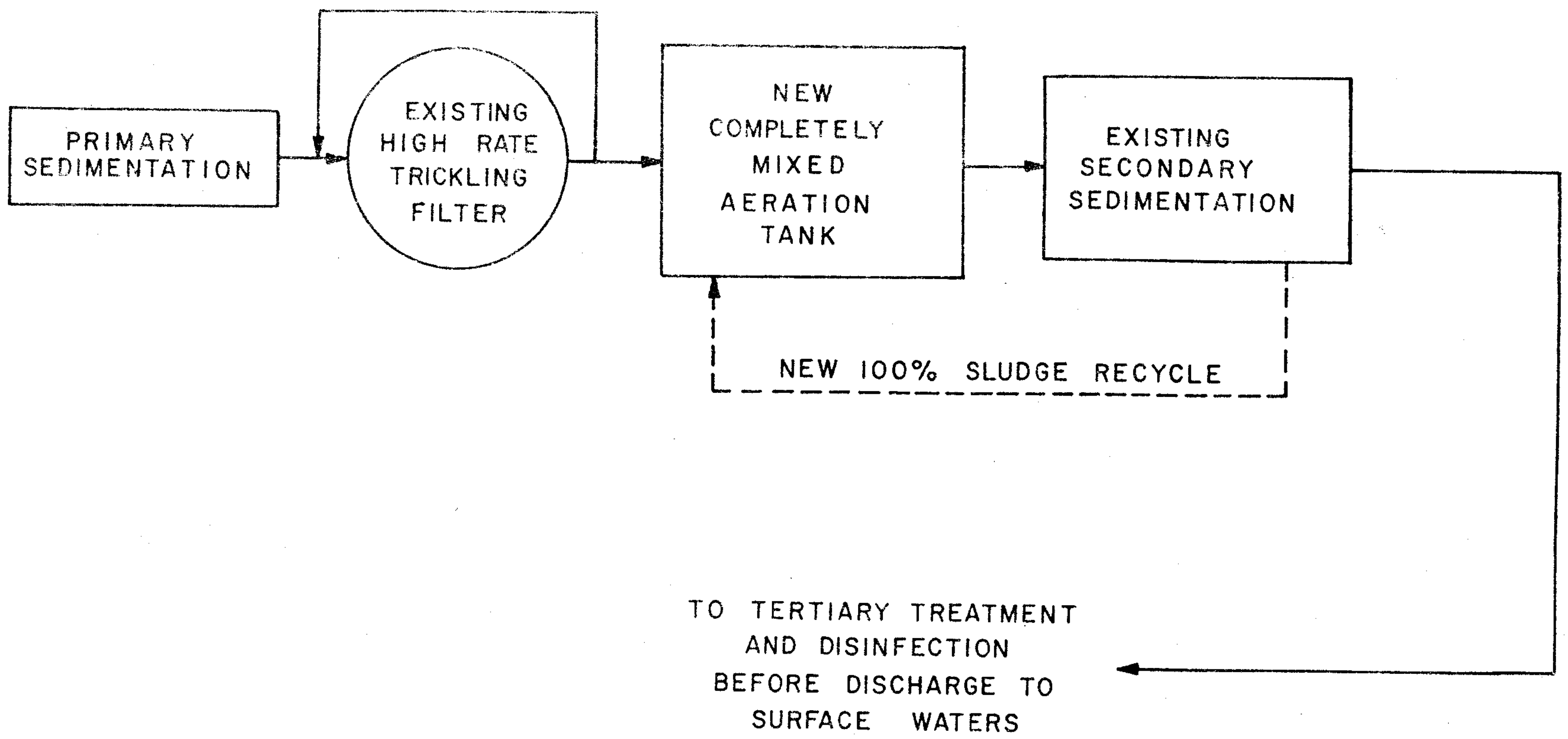


Figure VII-19. Trickling Filtration/Activated Sludge System

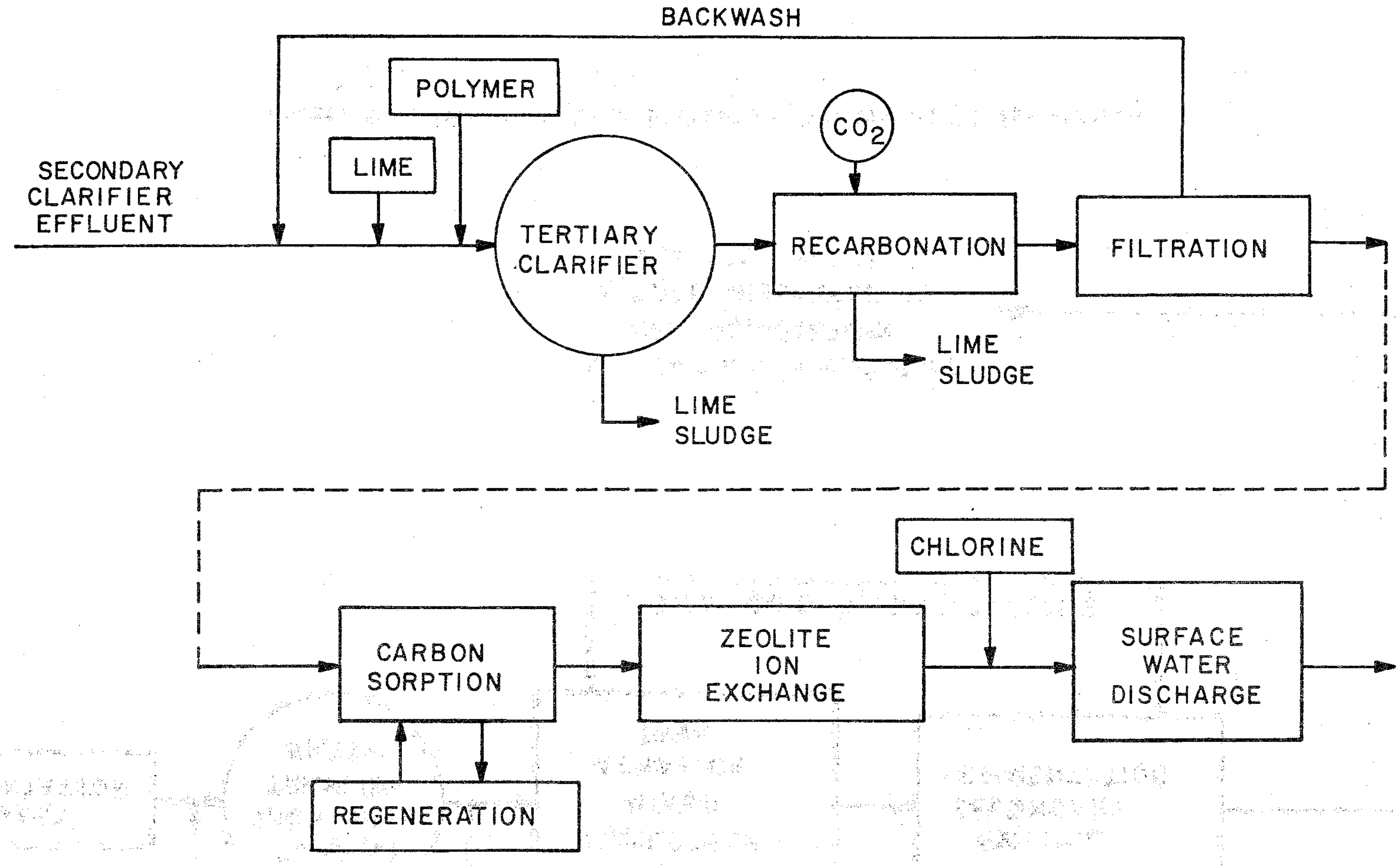


Figure VII-20. Added Tertiary Treatment Unit Processes, Incineration of Chemical Sludge

Northwest Laboratories.[19] Capital cost changes due to variations in plant size are approximated through use of the exponential rule:[19]

1. if plant size changes by a factor of X, the cost will change by a factor of X^N where N varies from 0.0 to 1.0, and

2. an average exponential factor of N = 0.6 is used, for wastewater treatment facilities and equipment designed for plants with 100 mgd (378,500 cu m/day) flow or less, as in the case for Des Moines, Iowa.

Capital costs presented in the Battelle Report are expressed in 1973 dollars (ENR≈1900). Capital costs presented in this section have been updated by multiplying the base cost by the ratio of the current (1975) ENR index (2200) to the 1973 index. Local cost multipliers were not available to adjust national average costs to figures reflecting the price structure likely to prevail in Des Moines. Thus, for example, a land value of $1000 per acre ($2500 per ha) has been assumed.

Operating costs may vary significantly from the estimates provided in this section as a result of local differences in costs for power, fuel, chemicals, labor, transportation, supervision and maintenance. An exponential rule is used to adjust approximately for variations in plant size as follows:

1. N = 0.58 for labor and supervision,

2. N = 0.55 for electrical, and

3. N = 1.00 for chemicals and fuel,

for flow rates up to 100 mgd (378,500 cu m/day). Total annual costs are then calculated by adding amortized capital costs to the operating and maintenance costs.

Capital costs are shown itemized in Table VII-7, Capital Costs for Tertiary and Intermediate-Stage Treatment. These figures do not include costs of primary and secondary treatment, as they pertain to already existing conditions in Des Moines. Operating costs are listed in Table VII-8, Operating Costs for Tertiary and Intermediate-Stage Treatment. The following assumptions are made:

1. overall costs of labor are $8 per man hour for an 8 hour day,

2. power costs are $0.025 per kilowatt-hour,

TABLE VII-7. CAPITAL COSTS FOR TERTIARY AND INTERMEDIATE-STAGE TREATMENT, 35.3 MGD (1.55 cu m/sec)

Item	Base Cost[b]	Scale Factor,[a] X^N	ENR Ratio	Adjusted Cost
1. Liquid Treatment	$\$4.7 \times 10^6$	$(3.53)^{0.6}$	$\frac{2200}{1900}$	$\$11.60 \times 10^6$
2. Liquid Disposal	0.043×10^6	2.13	1.16	0.11×10^6
3. Chemical Sludge	1.9×10^6	2.13	1.16	4.69×10^6
4. Organic Sludge	1.0×10^6	2.13	1.16	2.47×10^6
Land for (1.)	12,000	2.13	1.16	0.03×10^6
(3.)	21,000	2.13	1.16	0.05×10^6
(4.)	4,100	2.13	1.16	0.01×10^6
	TERTIARY CAPITAL EXPENDITURE			$ 18,960,000
	Intermediate-Stage Cost			+ 2,222,772
	TOTAL CAPITAL EXPENDITURE			21,182,772
	Amortization: 20 years at 8%			
	Amortized Annual Capital Cost =			$2,157,508

[a]See definition in text.

[b]Reference 19 (Strategy no. 9) for 10 mgd plant.

TABLE VII-8. OPERATING COSTS FOR TERTIARY AND INTERMEDIATE-STAGE TREATMENT, 35.3 MGD (1.55 cu m/sec)

Item	Base Cost[b]	Scale Factor,[a] X^N	Adjusted Cost
1. Base Labor		$3.53^{0.58}$	
(i) Liquid Treatment	214,912	2.08	$446,653/yr
(ii) Chemical Sludge	233,600	2.08	485,492
(iii) Organic Sludge	151,840	2.08	315,570
2. Electrical Power		$(3.53)^{0.55}$	
(i) Liquid Treatment	197,100	2.00	394,423
(ii) Chemical Sludge	29,337	2.00	58,707
(iii) Organic Sludge	16,516	2.00	33,051
3. Chemicals		$(3.53)^1$	
(i) Liquid Treatment			
a) Lime	153,300	3.53	541,149
b) CO_2	193,450	3.53	682,879
c) Cl_2	18,396	3.53	64,938
d) Polymer	15,330	3.53	54,115
(ii) Organic Sludge (Polymer)	146,000	3.53	515,380
4. Fuel		$(3.53)^1$	
(i) Liquid Treatment	3,164	3.53	12,756
(ii) Chemical Sludge	109,208	3.53	385,504
(iii) Organic Sludge	40,150	3.53	141,730
		TOTAL ANNUAL COST	$ 4,132,347

[a]See definition in text.

[b]Reference 19 (Strategy no. 9) for 10 mgd plant.

3. chlorine costs are $0.12 per pound ($0.26 per kg),

4. polymer costs are $2.00 per pound ($4.41 per kg),

5. lime costs are $0.02 per pound ($0.04 per kg),

6. CO_2 costs are $0.02 per pound ($0.04 per kg), and

7. fuel costs are $0.11 per therm ($0.11 per 1000 kg-calorie).

Transportation costs are not included since the sludge is assumed to be disposed on site by incineration. The total annual cost (including amortized capital cost) is $6,289,855. This figure represents a cost of $0.49 per 1000 gallons ($0.13 per cu m) for conversion to activated sludge from high-rate trickling filtration, the intermediate-stage and addition of tertiary treatment with incineration of chemical and organic sludges.

The tertiary treatment configuration shown in Figure VII-20 constitutes a rather complete and sophisticated process profile. Battelle-Pacific Northwest Laboratories recommends this strategy as an alternative to existing secondary activated sludge plants which are required to provide additional organic and nutrient removal.[19] Furthermore, such a process configuration will produce a higher quality effluent than any of the other strategies considered.[19] However, examination of Tables VII-7 and VII-8 reveals that the incremental cost of providing such a facility is quite high. If organic waste removal is the primary consideration, a lower cost control strategy may be considered: activated sludge-coagulation-filtration (Battelle Northwest, 1974; Strategy 8).[19]

Assuming that the intermediate-stage conversion has been accomplished (see Figure VII-19), an alternative to complete tertiary treatment is shown in Figure VII-21, Activated Sludge-Coagulation-Filtration Process Profile. This control strategy compares favorably with the more advanced option in BOD removal capabilities. Treatment plant efficiencies vary considerably with the input flow rate and waste concentration. Battelle assumed a medium strength sewage of 200 mg/1.[19] For 10 mgd (38,000 cu m/day), 100 mgd (380,000 cu m/day) and 1000 mgd (3,800,000 cu m/day) plant sizes BOD removal efficiencies up to (1) 99 percent for tertiary treatment, and (2) 98 percent for activated sludge-coagulation-filtration are given.

In general terms, any type of post-secondary treatment (other than chlorine disinfection) is classified as tertiary treatment in the water pollution control literature. The option depicted by Figure VII-21 has been assumed as a type of tertiary treatment and exclusively referred to

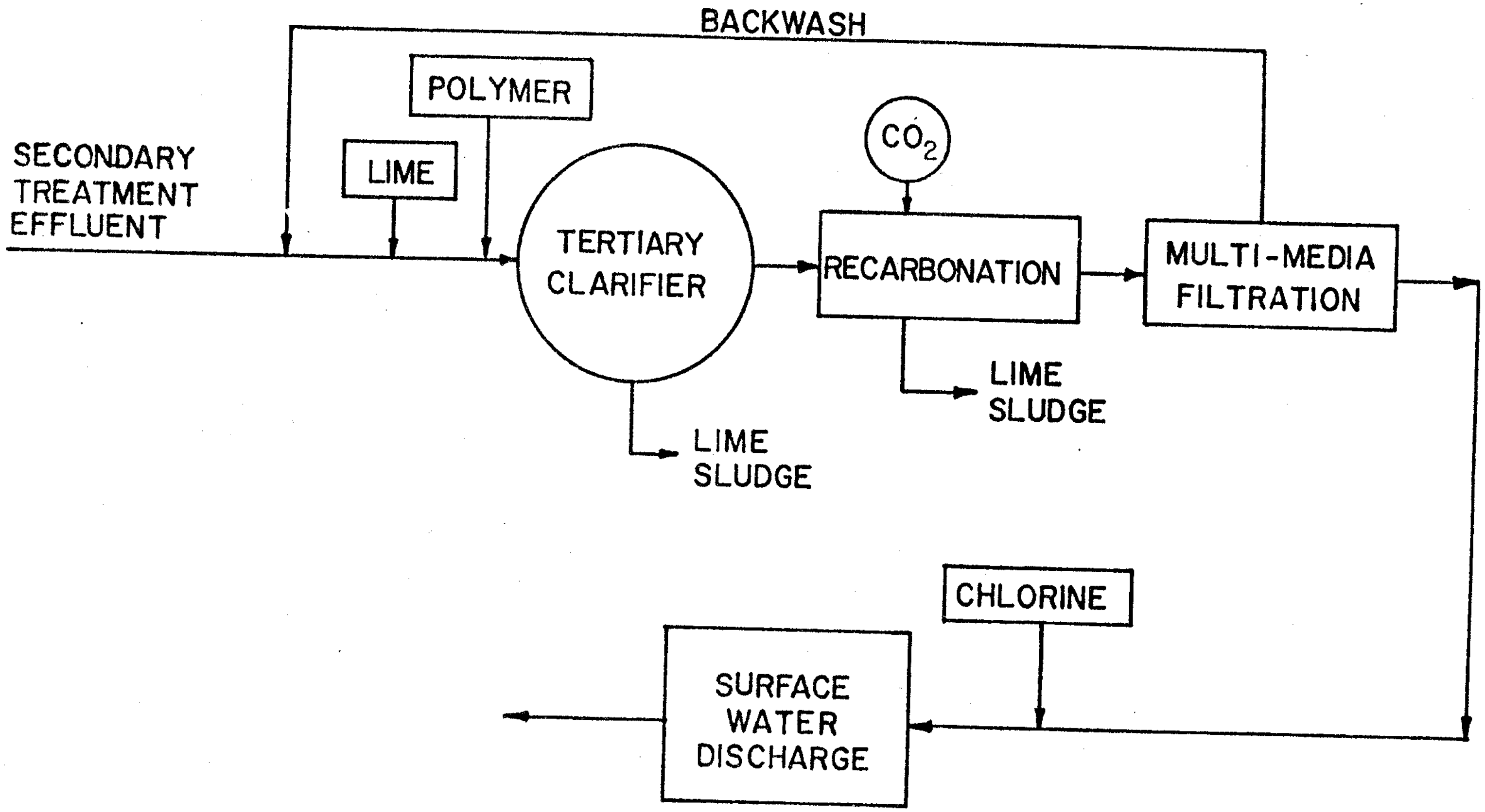


Figure VII-21. Activated Sludge-Coagulation-Filtration Process Profile as such in the analysis presented in Section VI. The more descriptive title is used in this section to distinguish the process from the more advanced profile of Figure VII-20. It is appropriate to emphasize that the type of post-secondary DWF process adopted by a municipality will depend on such local factors as sewage characteristics, energy resources, and receiving water quality.

The incremental cost of providing the facilities of an activated sludge-coagulation-filtration system may be estimated by:[20]

$$C_{tert} = 87{,}000\ D_p^{0.787} \qquad \text{(VII-36)}$$

where C_{tert} = annual cost, dollars, including amortized capital costs (20 years, 8 percent) and operating and maintenance costs, and

D_p = plant size, mgd.

Total annual costs of both types of post-secondary treatment are summarized in Table VII-9, Dry-Weather Flow Costs for Advanced Treatment. The amortized capital cost of intermediate-stage conversion has been added to the cost computed by equation VII-36 for the activated sludge-coagulation-filtration design. The large difference in annual costs is due to:

1. the added expense for chemicals during ammonia removal, and

2. added fuel costs during incineration of chemical and organic sludges,

for the complete tertiary treatment configuration.

Control of Urban Runoff

The methodology for assessing the cost of providing storage/treatment facilities for wet-weather flows is presented in Section VI. A basic assumption is that a secondary treatment technology is applied to achieve four levels of control for the total BOD generated by urban runoff: 25, 50, 75 and 85 percent BOD removal. Various control alternatives were evaluated: dissolved air flotation, biological treatment, physical-chemical treatment and sedimentation.[21]

The cost of wet-weather control for the storm sewered area of Des Moines, Iowa, may be estimated by (Table VI-10):

$$Z_{ST} = 3.61\ e^{0.037R_1} \qquad \text{(VII-37)}$$

Table VII-9. DRY-WEATHER FLOW COSTS FOR ADVANCED TREATMENT[a]

Type	Total Annual Cost[b]
1. Complete Tertiary Treatment	$6,290,000
2. Activated Sludge-Coagulation-Filtration	$1,664,000

[a]For plant size 35.3 mgd (1.55 cu m/sec).

[b]Includes amortized capital costs, operating and maintenance costs, and intermediate-stage conversion.

Table VII-10. WET-WEATHER FLOW CONTROL COSTS[a]

R_1 % BOD Removal	Storm Sewer Area Cost, Z_{ST} \$/acre (\$/ha)	Combined Sewer Cost, Z_{CO} \$/acre (\$/ha)	Total Annual Cost
25[b]	9.10 (22)	101.66 (251)	$ 816,000
75[b]	57.90 (143)	1671.83 (4128)	$9,293,000

[a]Based on 49,000 acres (19,600 ha) of developed urban area.
[b]Approximate solution. See Section VI for details.

where Z_{ST} = annual cost, dollars per acre of storm sewer area, and

R_1 = percent BOD control,

and

$$0 \leq R_1 \leq 85. \qquad \text{(VII-38)}$$

The cost of wet-weather control for the urban area served by combined sewers may be approximated by (Table VI-9):

$$Z_{CO} = 25.07\, e^{0.056R_1} \qquad \text{(VII-39)}$$

where Z_{CO} = annual cost, dollars per acre of combined sewer area.

These equations yield unit costs, not total costs, but they are derived by a procedure that estimates the total developed acreage of an urban area (see Section VI). The average annual runoff associated with equations VII-37 and VII-39 is 11.2 inches (284 mm), computed from a mean annual precipitation of 30.37 inches (771 mm). The length of the precipitation records is 30 years (1931-1960).[22]

The cost figures for 25 percent and 75 percent BOD removal of WWF are presented in Table VII-10, Wet-Weather Flow Control Costs. These values are based on a total drainage area of 49,000 acres (19,600 ha), of which 45,000 acres (18,000 ha) are served by separate sewers and 4,000 acres (1,600 ha) are served by combined sewers. The annual runoff for 1968 for Des Moines, Iowa, is 10.28 inches (261 mm); thus, the unit costs obtained from equations VII-37 and VII-39 are slightly high but an adjustment is not considered necessary. The total annual costs shown in Table VII-10 include amortized capital costs and annual operating and maintenance costs.

Tradeoff in Alternatives

To view the control strategies in the proper perspective, the status quo conditions are included as a base for comparisons. Any alternative plans that depart from this base must be justified on their cost-effectiveness. Thus, the cost figures shown in Table VII-11, DWF Tertiary Treatment vs WWF Control, represent the additional expense incurred in providing storage/treatment beyond that already available with secondary treatment of DWF and no control of urban runoff. Figures VII-15, VII-16 and VII-17 show the effects of various control strategies upon the minimum DO concentrations of the Des Moines River.

Table VII-11. DWF TERTIARY TREATMENT VS WWF CONTROL

Options	Amortized Annual Capital Cost $ (20 yrs, 8%)	Operation and Maintenance Cost ($/yr)	Total Annual Cost ($/yr)
1. DWF Complete Tertiary Treatment, No WWF Treatment	2,158,000	4,132,000	6,290,000
2. DWF Activated Sludge-Coagulation-Filtration, No WWF Treatment	---	---	1,664,000
3. WWF 75% BOD Removal, DWF Secondary Treatment	---	---	9,293,000
4. WWF 25% BOD Removal, DWF Secondary Treatment	---	---	816,000

[a] Based on 49,000 acres (19,600 ha) of developed urban area. The total annual cost computed by equations VII-37 and VII-39 includes amortized capital cost (20 yrs, 8%) and operation and maintenance costs.

The Des Moines River stretches for 200 miles (322 km) from the City of Des Moines to its junction with the Mississippi River and, in general, the river is wide and swift with occasional deep holes and a broad flood plain. According to the State Hygienic Laboratory, bottom material is composed of silt deposits, sand, gravel and rubble providing numerous habitats for fish and other aquatic life. Recreational activities such as fishing and boating are quite heavy. The entire reach is classified as warm water "B" stream by the Iowa Water Quality Standards,[23] such that the absolute minimum dissolved oxygen level specified is 4.0 mg/l. The Iowa Standards also require a minimum of 5.0 mg/l during at least 16 hours per day.[24] Thus, taking 4.0 mg/l as the standard or basis for water quality comparisons, the different control options may be judged by the following criteria:

1. total annual cost, and

2. violations of the minimum allowable dissolved oxygen level.

Table VII-12, Control Costs vs Violations of the DO Standard, summarizes the cost-effectiveness of two advanced waste treatment options, two wet-weather control options, and existing DWF secondary treatment facilities. For comparative purposes, two additional treatment conditions which are not presently acceptable by government regulation are presented.

Examination of Figures VII-15, VII-16, VII-17 and Table VII-12 reveals that:

1. since both types of tertiary treatment remove essentially the same amount of BOD, option 1 is justified over option 2 only when nutrient removal is necessary;

2. option 4 is preferred over any form of advanced waste treatment;

3. option 3 is attractive because it causes the least amount of damage to the receiving stream, but it is the most expensive alternative; and

4. any reduction in the degree of DWF treatment for existing conditions, option 5, results in a substantial deterioration to receiving water dissolved oxygen levels and must be weighed against the savings incurred.

Table VII-12. CONTROL COSTS[a] VS VIOLATIONS OF DO STANDARD[b]

Options	% Wet-Weather Events[c] Violating Standard	% Dry Days in Year Violating Standard	Total Incremental Annual Cost ($/yr)	Total No. of Days During Year that DO Standard is Violated
1. DWF Complete Tertiary Treatment, No WWF Treatment	40	1.5	6,290,000	31
2. DWF Activated Sludge Coagulation-Filtration Treatment, No WWF Treatment	40	1.5	1,664,000	31
3. DWF Secondary Treatment, WWF 75% BOD Removal	3	2.0	9,293,000	8
4. DWF Secondary Treatment, WWF 25% BOD Removal	30	2.0	816,000	26
5. DWF Secondary Treatment, No WWF Treatment	42	2.0	0	33
6. DWF Primary Treatment, No WWF Treatment	50	3.0	-1,438,000[d]	42
7. No DWF Treatment, No WWF Treatment	53	7.0	-1,843,000[d]	55

[a] In addition to control costs for existing conditions (5).

[b] Based on a minimum allowable DO concentration of 4.0 mg/1.

[c] Defined by a minimum interevent time of 9 DWH.

[d] Savings incurred by reducing DWF treatment of trickling filter plant of 35.3 mgd (1.55 cu m/sec).

Again, the issue of shock loads is important, and favors high levels of WWF control.

The reader should be cautioned that advanced tertiary treatment is rarely imposed just to improve the BOD removal capabilities of existing facilities. It is usually designed specifically for nitrogen and/or phosphorus removal. For the heavy precipitation months of June, July and August, 1968, Davis and Borchardt[9] reported the following nutrient concentrations at a point approximately 5.5 miles (9.0 km) downstream from the confluence of the Raccoon and Des Moines Rivers:

1. total organic nitrogen ranged from 1.6 to 3.7 mg/l,

2. nitrate nitrogen ranged from 0.2 to 7.8 mg/l, averaging 3 to 4 mg/l, and

3. orthophosphate (OPO_4) ranged from 0.6 to 1.8 mg/l, averaging slightly over 1.0 mg/l.

Since most of the urban runoff would overflow untreated to the receiving water, any program of advanced treatment given to all urban DWF would be relatively ineffective. It would also be questionable whether a level of WWF control consisting of secondary treatment (such as that evaluated for 75 percent BOD removal) could reduce nutrient levels in the Des Moines River and Red Rock Reservoir to inhibit aquatic plant growth. Davis and Borchardt[9] observed high algal densities in both the Des Moines and Raccoon Rivers, and they also state that nutrient concentrations are almost always present at levels reported by Sawyer[25] to be sufficient for nuisance algal growths: 0.3 mg/l for inorganic nitrogen (NH_3, NO_2, NO_3) and 0.015 mg/l of inorganic phosphorus. Furthermore, since nitrates are abundant in groundwater and the surface and subsurface hydrologic systems are not independent of each other, nutrient control seems highly complex and improbable.[26]

The total annual precipitation for the year 1968 was 27.59 inches (701 mm). The frequency and intensity of precipitation over an urban area has a direct bearing on the magnitude of stormwater pollution and, consequently, dissolved oxygen levels in the receiving water. In the selection of the "best" control strategy, other factors may become important, such as:

1. recovery of receiving waters from shock loads during runoff periods,

2. local and regional water quality goals,

3. public willingness to pay the costs associated with each level of control, and

4. consideration of alternate use of WWF facilities as DWF treatment facilities during periods of no urban runoff.

In general, although selection of a storage/treatment configuration involves many factors it is important to note that the impact of urban stormwater runoff must be evaluated. Davis and Borchardt[9] compared daily pollutant loadings (BOD, NO_3, PO_4) from storms ranging in size from 0.175 inch (4.4 mm) to 6 inches (152.4 mm) in total depth to those from dry-weather sources in the Des Moines metropolitan area. In all cases, the loads derived from urban runoff exceeded greatly the average daily loads from dry-weather sources.

OTHER RECENT RECEIVING WATER IMPACT STUDIES

Black, Crow & Eidsness, Inc., and Jordan, Jones & Goulding, Inc., evaluated non-point pollution sources in the Atlanta metropolitan area and their impact on the dissolved oxygen (DO) levels in the Chattahoochee River.[27] Only two sources of urban stormwater runoff were reported as significant: combined sewer overflows and unsewered urban runoff (natural collection systems). On an annual basis, these sources accounted for about 45 percent of the BOD load (lbs/yr) and about 95 percent of the suspended solids load to metropolitan Atlanta streams, assuming that all point sources were receiving secondary treatment.

A steady-state mathematical model (developed by the Georgia Department of Natural Resources Environmental Protection Division) was applied to simulate the effects of a 0.4 inch (10.2 mm) rainstorm, with a two-hour duration of runoff, assumed to fall over all combined sewer overflow drainage areas.[27] It was also assumed that all point source (DWF) wastewater treatment plant effluents met state fish and wildlife standards. The results of the simulation indicate that such a rainstorm would violate stream DO standards in the Chattahoochee River for over 50 miles (80 km) downstream, with a minimum DO concentration of zero for a period of approximately 12 hours. The 0.4 inch rainstorm (upper limit of summer thunderstorm size in the Atlanta area) over any one of the combined sewer overflow areas would apparently cause a similar violation for a two-hour period. The impact of unsewered urban runoff on water quality in the Chattahoochee River was also determined by simulation of a rainfall event over the entire Peachtree Creek basin (highly urbanized). The storm selected was again 0.4 inch (10.2 mm) in rainfall volume but its duration was assumed to be 10 hours. The Corps of Engineers' model STORM was utilized to simulate the quantity and quality of the surface washoff. Output from STORM was routed down the Chattahoochee River using the model DOSAG (Texas Water Development Board).[31] Violations of the fish and wildlife standard, 5.0 mg/l of dissolved oxygen, were predicted for over 40 miles (64 km) downstream and the minimum dissolved oxygen concentration was computed to be 1.4 mg/1.

Hydrocomp International (Palo Alto, California) conducted dynamic simulation of a large watershed in the South Platte River basin for Black & Veatch and the Denver Regional Council of Governments.[28] The 750 square mile (194,256 ha) area included metropolitan Denver within its boundaries. Simulations of streamflow and stream water quality conditions for given precipitation, wastewater loadings, and diversions (irrigation) were performed for each of several proposed wastewater system configurations. The water quality calibration process to adapt the Hydrocomp Simulation Program (HSP) to actual environmental conditions was hindered by the lack of a continuous data base within the designated study area, a problem prevalent throughout the nation. An analysis of a 20-year simulation for one plant configuration indicated that the calendar year 1954 represented one of the most critical periods from a water quality standpoint. It had the lowest annual streamflow for the 20-year historical record, and some of the lowest stream dissolved oxygen concentrations were predicted.

The Hydrocomp study did not specifically address urban stormwater control facilities as a treatment alternative. Five levels of wastewater treatment (DWF) were tested for the critical year: (1) secondary, (2) secondary with filtration, (3) secondary with nitrification, (4) tertiary and (5) zero pollutants discharged. Daily duration curves were computed for minimum dissolved oxygen for each DWF treatment level. Of the five levels, the effluents from secondary treatment with nitrification, tertiary treatment, and absolute treatment (zero pollutant discharge from DWF sources, financially prohibitive) did not exceed the stream standards imposed by the regulatory agency. Treatment levels 3 and 4 were thus considered the only acceptable options from an effluent viewpoint. Three possible treatment plant discharge configurations were tested at these two treatment levels. The resulting minimum daily DO duration curves (such as Figure VII-6) were practically identical.

From the DO duration curves for zero pollutant discharge from dry-weather sources, some interesting inferences may be drawn on the effects of urban runoff. The average annual precipitation over the study area for the period 1935-1974, was 14.58 inches (370 mm), less than half the national average.[29] The entire modeling area may be classified as semi-arid. The total annual precipitation for the critical year 1954 was 7.51 inches (190 mm), or about one-fourth of the total annual precipitation recorded in 1968 over Des Moines, Iowa. The minimum daily DO duration curve for the zero pollutant discharge (DWF) treatment level was entirely above the minimum DO standard, 5.0 mg/1, for the reach of the South Platte River below the Denver metropolitan area. This curve represents the minimum daily DO concentration history of the receiving stream resulting exclusively from the urban runoff waste input. Thus, the urban runoff pollutant load for the drought year 1954 was insufficient to drive the critical DO levels below the fish and wildlife standard. The cost of stormwater control would not be justified.

Hydrocomp also prepared an evaluation of the effects of urbanization on aquatic ecology and hydrologic regimes for the Office of Water Research and Technology, Department of the Interior.[30] Urbanization affects flood frequency, flow duration, total volume of runoff, and has an impact because of additional pollutant load on stream BOD, DO, and nutrient concentrations. Computer simulation was employed to generate synthetic data series in the absence of historic series for three hypothetical cities representing the Pacific Northwest, eastern slope of the Rocky Mountains, and the central Atlantic states. Of particular interest is a comparison among these regions of the effect of urbanization on: (1) surface runoff quantity (Table VII-13, Increase in Surface Runoff), and (2) pollutant loadings (Table VII-14, Increase in Annual BOD Mass Discharge). The hypothetical watersheds consisted of a drainage area of 60 square miles (155.4 sq km) having all of the land surface characteristics of the test watersheds (for which HSP was regionally calibrated), including impervious area. For the urbanized case, the lower half of each watershed was assumed to be intensively urbanized with 35 percent imperviousness and directly connected to the stream system. The hydrologic period of study extended from 1948 to 1972. The average percent increase of annual runoff due to urbanization was much greater for the arid watershed. For the very wet watershed, the Pacific Northwest, high soil moistures resulted in almost as much runoff from rural land as from impervious (urban) areas. A substantial increase in peak flows was observed for one year return period events. Again, the percentage increase in peak flows due to increased imperviousness was observed to decrease from arid to wet regions. For the 25-year peak flows, the percent increase due to urbanization was slight. This, of course, is largely due to the magnitude of these events. It is interesting to note from Table VII-14 that the annual BOD mass discharge was increased at least 100 percent by urbanization.

CONCLUSIONS

A methodology has been presented in Section VII to assess the relative importance of separate, combined, and DWF sewer runoff as waste sources generated by the urban environment. The effects of WWF and DWF pollutants on the minimum DO levels of an urban stream are presented on a frequency basis. The application to Des Moines, Iowa, demonstrated clearly the significant effect of urban runoff pollution on critical DO concentrations in the Des Moines River. The cost-effectiveness of various wastewater treatment alternatives can be determined realistically only by a continuous model which shows the frequency of water quality violations in the receiving stream.

Table VII-13. INCREASE IN SURFACE RUNOFF (Hydrocomp, 1975)[30]

Basin	Mean Annual Precipitation in (mm)	% Increase Annual Runoff	% Increase Peak Flows 1 yr-25 yr
Eastern Slope Rocky Mountains	18.2 (462.0)	91	2800 - 9
Central Atlantic	43.5 (1105.0)	53	1460 - 4
Pacific Northwest	56.2 (1427.0)	10	1200 - 1

Table VII-14. INCREASE IN ANNUAL BOD MASS DISCHARGE (Hydrocomp, 1975)[30]

Basin	Rural BOD lbs/yr (kg/yr)	Urban BOD lbs/yr (kg/yr)	Urban/Rural Ratio
Eastern Slope Rocky Mountains	0.65×10^5 (0.29×10^5)	2.1×10^5 (0.95×10^5)	3.2
Central Atlantic	1.30×10^5 (0.59×10^5)	3.0×10^5 (1.36×10^5)	2.3
Pacific Northwest	2.10×10^5 (0.95×10^5)	4.4×10^5 (2.00×10^5)	2.1

For 1968, 65 days of rainfall were recorded over Des Moines, Iowa, from which 58 wet-weather events were defined according to a minimum interevent time of nine dry-weather hours. The annual precipitation total was 27.59 inches (701 mm), producing 10.28 inches (261 mm) of urban runoff. For existing treatment facilities, 42 percent of the wet-weather events were predicted to violate a 4.0 mg/l DO standard, as well as two percent of all the dry-weather days. Thus, the model predicted that violations of such a standard would occur 33 days out of the year. The highest control strategy would reduce the number of days to eight, at an incremental cost of $9 million. The most cost-effective alternative seems to be 25 percent control of WWF and secondary treatment of DWF, at a cost of $816,000 per year, and resulting in stream standard violations 26 days out of the year.

The methodology that has been applied to the Des Moines urban area should serve as a decision-making tool for planning purposes only. Other models exist that are better suited for the intent of design and operation. In spite of the use of simplified mathematical modeling techniques, close agreement was achieved with field measured data through verification analysis, and the primary purpose of the modeling effort was accomplished. The reader should review the numerous assumptions which were an integral part of model development and application and should understand that the final numbers obtained are intended as a guide for screening alternatives.

ABBREVIATIONS AND SYMBOLS

A_c	Area served by combined sewers, acres
A_s	Area served by separate sewers, acres
A_t	Total area of catchment, acres
AR_u	Urban area runoff, inches per hour
α_1, α_2	Regression coefficients
B	Benthal demand of bottom deposits, mg per 1-hour
BOD	Biochemical oxygen demand, mg/1
BOD_5	Standard BOD test, 5 days at 68°F (20°C), mg/1
BOD_c	Mixed BOD concentration in the combined sewer, mg/1
BOD_d	BOD concentration of wet-weather flow treatment facility effluent, mg/1
BOD_f	BOD concentration of municipal sewage, mg/1
BOD_m	Mixed BOD concentration in receiving water, mg/1
BOD_s	BOD concentration of urban stormwater runoff, mg/1
BOD_t	Hourly BOD concentration of total urban runoff, mg/1
BOD_u	Mixed BOD concentration from sources upstream of urban area, mg/1
BOD_w	BOD concentration of treated wet-weather effluent, mg/1
β_1, β_2	Regression coefficients
C	Concentration of water quality parameter, M/L^3
C	Concentration of dissolved oxygen (DO) in the stream, mg/1
C_{min}	Concentration of DO at maximum deficit, mg/1
C_s	Saturation concentration of DO, mg/1
C_1	Conversion factor, pounds per hour to mg/1 · cfs
C_{tert}	Annual cost of activated sludge-coagulation-filtration system, dollars
CBOD	Carbonaceous biochemical oxygen demand

COD	Chemical oxygen demand
CR_u	Composite runoff coefficient dependent on urban land use
D	Dissolved oxygen deficit = $C_s - C$, mg/l
D_c	Critical (maximum) deficit, mg/l
D_u	DO deficit in receiving waters upstream of inflow point, mg/l
D_o	Initial DO deficit, mg/l
D_p	Size of activated sludge-coagulation-filtration plant, mgd
DO	Dissolved oxygen
DWF	Dry weather flow, cfs
DWFSEP	Dry-weather flow contribution from separate sewer area, cfs
DWFCMB	DWF contribution from combined sewer area, cfs
DWH	Number of dry-weather hours preceding each runoff event
E	Longitudinal dispersion coefficient, $feet^2$ per second
ENR	Engineering News Record Cost Index
f	Self-purification ratio, K_2/K_1
f_u	Available urban depression storage, inches
FF	First flush BOD load, pounds per hour
FFLBS	First flush factor, pounds/hour per DWH-acre
H	Stream depth, feet
k	Number of hourly lags
K_n	Oxidation coefficient of nitrogenous BOD, $hours^{-1}$
K_1	Deoxygenation constant of carbonaceous BOD, $hours^{-1}$
K_2	Atmospheric reaeration coefficient, $hours^{-1}$
L	Remaining carbonaceous BOD concentration, mg/l
L_o	Mixed BOD concentration in the river, mg/l
$(L_o)_c$	Ultimate first-stage BOD demand, mg/l

n	Total number of data points or observations of a hydrologic process
N_n	Remaining nitrogenous BOD concentration, mg/l
N	Exponent in scale factor
NBOD	Nitrogenous biochemical oxygen demand
OPO_4	Orthophosphate
P	Oxygen production rate by algal photosynthesis, mg/l-hour
P_u	Hourly rainfall/snowmelt in inches over the urban area
Q	Streamflow, cfs
Q_c	Combined sewer flow, cfs
Q_d	DWF treated effluent, cfs
Q_s	Urban runoff carried by the separate storm sewer, cfs
Q_t	Total (storm plus combined) urban runoff, cfs
Q_u	Upstream flow, cfs
Q_w	Wet-weather flow (WWF) treated effluent, cfs
R_1	Percent BOD control (removal) by wet-weather storage-treatment
R_d	Fraction removal of BOD achieved by the DWF treatment facility
R_e	Algal respiration rate, mg/l-hour
$r_I(k)$	Sample estimate of lag-k autocorrelation coefficient for rainfall
R_o	Deficit load ratio = D_o/L_o
$r_Q(k)$	Sample estimate of lag-k autocorrelation coefficient for runoff
R_w	Fraction removal of BOD achieved by the WWF treatment facility
S	Sources and sinks of the substance C, M/L^3T
T	Stream temperature, °C
t	Time, hours or days
t_c	Elapsed time at which critical deficit occurs, hours or days

TL(95%)	Tolerance limits at a 95 percent probability level
TOC	Total organic carbon
TSS	Total suspended solids
U	Flow velocity in stream, feet per second
$\forall$	Volume of DO deficit, mg-hours/l or mg-day/l
WWF	Wet-weather flow, cfs
x	Distance downstream, feet or miles
x_1	Discrete data series (observations) of a hydrologic process
X	Scale factor
Z_{CO}	Optimal annual cost of wet-weather control for combined sewered areas, dollars per acre
Z_{ST}	Optimal annual cost of wet-weather control for storm sewered areas, dollars per acre

REFERENCES

1. Geraghty, J. J., et al., Water Atlas of the United States, Water Information Center, Inc., Port Washington, NY, 1973.

2. Murray, C. R. and Reeves, E. B., "Estimated Use of Water in the United States in 1970," USGS Circular 676, 1972.

3. US Department of Agriculture, "Major Uses of Land and Water in the United States with Special Reference to Agriculture: Summary for 1964," Econ. Rept. 149, 1968.

4. Medina, M. A., Jr., "Data Needs for Stormwater Treatment and Control," Proceedings of Third Annual Environmental Short Course, Florida Engineering Society, Lake Buena Vista, Florida, October, 1974.

5. Liptak, Bela G., Environmental Engineers' Handbook, Vol. 1: Water Pollution, Section 2.10, Chilton Book Company, Radnor, PA, 1974.

6. American Public Health Association, Standard Methods for the Examination of Water and Wastewater, 13th Edition, Washington, DC, 1971.

7. Nemerow, N. L., Scientific Stream Pollution Analysis, McGraw-Hill Book Company, NY, 1974.

8. Hydrologic Engineering Center, Corps of Engineers, "Urban Stormwater Runoff: STORM," Generalized Computer Program 723-58-L2520, 1975.

9. Davis, P. L. and Borchardt, F., "Combined Sewer Overflow Abatement Plan," USEPA Report EPA-R2-73-170, April, 1974.

10. Yevjevich, V., Stochastic Processes in Hydrology, Water Resources Publications, Fort Collins, CO, 1972.

11. Fiering, M. B. and Jackson, B. B., Synthetic Streamflows, Water Resources Monograph 1, American Geophysical Union, Washington, DC, 1971.

12. Quimpo, R. G., "Autocorrelation and Spectral Analyses in Hydrology," J. Hyd. Div., Proc. ASCE, Vol. 94, No. HY2, pp. 363-373, March 1968.

13. Hydroscience, Inc., "Simplified Mathematical Modeling of Water Quality," USEPA, March 1971.

14. ASCE, Committee on Sanitary Engineering Research, "Solubility of Atmospheric Oxygen in Water," JSE Div., Proc. ASCE, Vol. 86, No. SA4, pp. 41-53, July 1960.

15. Langbein, W. B. and Durum, W. H., "The Aeration Capacity of Streams," USGS Circular 542, 1967.

16. Leopold, L. B. and Maddock, T., "The Hydraulic Geometry of Stream Channels and Some Physiographic Implications," USGS Professional Paper 252, 1953.

17. Arbabi, M. et al., "The Oxygen Sag Equation: New Properties and a Linear Equation for the Critical Deficit," Water Resources Research, Vol. 10, No. 5, pp. 921-929, October 1971.

18. Krishnan, P. and Mangan, C. M., Roy F. Weston, Inc., "Process Design Manual for Upgrading Existing Wastewater Treatment Plants," USEPA Technology Transfer, October 1971.

19. Battelle-Pacific Northwest Laboratories, "Evaluation of Municipal Sewage Treatment Alternatives," Council of Environmental Quality, NTIS-PB 233 489, February 1974.

20. Hasan, S. M., Integrated Strategies for Urban Water Quality Management, PhD Dissertation, University of Florida, Gainesville, 1976.

21. Lager, J. A. and Smith, W. G., "Urban Stormwater Management and Technology: An Assessment," USEPA Report EPA-670/2-74-040, NTIS-PB 240 687/AS, December 1974.

22. Waite, P. J., "The Climate of Iowa," Climates of the States, Vol. II, Water Information Center, Inc., Port Washington, NY, 1974.

23. State Hygienic Laboratory, "Des Moines River - Limnology Study," Report submitted to the Department of Environmental Quality and the Iowa Water Quality Commission, April 1974.

24. State Hygienic Laboratory, "Water Quality Survey of the Des Moines River," Report submitted to the Iowa Pollution Control Commission, October 1970.

25. Sawyer, C. N., "Basic Concepts of Eutrophication," JWPCF, Vol. 38, No. 5, pp. 737-744, May 1966.

26. Sawyer, C. N., "The Need for Nutrient Control," JWPCF, Vol. 40, No. 3, pp. 363-370, March 1968.

27. Black, Crow & Eidsness, Inc. and Jordan, Jones & Goulding, Inc., "Non Point Pollution Evaluation - Atlanta Urban Area," Report to US Army Corps of Engineers, Savannah District, GA, January 1975.

28. Black and Veatch, "Volume II -- Hydro Quality Model Report," Denver Regional Council of Governments, Water Quality Management Program Project No. IGA-00034, May 1974.

29. Private Communication, National Oceanic and Atmospheric Administration, Asheville, NC, September 1975.

30. Hydrocomp, Inc., "Evaluation of the Effects of Urbanization on Aquatic Ecology and Hydrologic Regimes," Office of Water Research and Technology, Contract No. 14-31-001-4203, July 1975.

31. Texas Water Development Board, "DOSAG-I Simulation of Water Quality in Streams and Canals, Program Documentation and User's Manual," Austin, Texas, NTIS-PB 202 974, September 1970.